AN EXPERIMENTAL AND MODELING SYNTHESIS TO DETERMINE SEASONALITY OF HYDRAULIC REDISTRIBUTION IN SEMI-ARID REGION WITH MULTISPECIES

BY

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THESIS

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ABSTRACT

A key challenge in critical zone science is to understand and predict the interaction between aboveground and belowground eco-hydrologic processes. Roots play an important role in linking aboveground plant ecophysiological processes, such as carbon, water and energy exchange with the atmosphere, and the belowground processes associated with soil moisture and carbon, and microbial and nutrient dynamics. In this study, I have analyzed aboveground and belowground interaction through hydraulic redistribution (HR), a phenomenon that roots serve as preferential pathways for water movement from wet to dry soil layers. HR process is simulated by multi-layer canopy model (MLCan) and compared with relative measurements from the field to study effect of HR on different plant species where *Posopis velutina Woot.* (velvet mesquite) and understory co-exist and share resources. The study site is one of Ameriflux sites: Santa Rita Mesquite savanna, AZ, with a distinct dry season that indicates occurrence of HR. The model is modified to better represent Santa Rita Mesquite site where fractions of plants and soil coverage change from season to season.

I analyzed how two plants share and utilize the limited amount of water by HR in both dry and wet seasons. During dry season, water moves from deep layer to shallow layer through roots and hydraulic lift (HL) occurs. During wet season, water moves from shallow layer to deep layer through roots and hydraulic descent (HD) occurs. Mesquites deposit water to deeper soil through their roots right after rain to prevent water loss due to surface evaporation. About 40% of precipitation is transferred to deep soil layer with HD and 15% of that is transported back to shallow soil layer with HL in dry season. Assuming water supplied through HL supports evapotranspiration of plants, HL supports 10% of evapotranspiration. The ratio of mesquite and understory root conductivities is an important factor that determines how two plant species interact and share resources in water-limited environment. The sensitivity analysis of root conductivities suggests that high understory root conductivity facilitates water transported by HR

and increases mesquite transpiration and photosynthesis. Understory transpiration and photosynthesis show increase with HR only in dry season when water is supplied to shallow layer through HL. With low understory root conductivity, understory looses the competition for water against mesquite and show decrease in transpiration and photosynthetic fluxes when HR is allowed.

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LIST OF ABBREVIATIONS

Symbol	Description [Units]
1-D	One-dimensional
2-D	Two-dimensional
AZ	Arizona
ET	Evapotranspiration [mm]
G	Ground heat flux [W/m^2]
H	Sensible heat flux [W/m^2]
HD	Hydraulic Descent
HL	Hydraulic Lift
HR	Hydraulic Redistribution
K_{ax}	Root hydraulic conductivity of root system in axial direction [mm/s]
K_s	Soil hydraulic conductivity
K_{rad}	Root hydraulic conductivity of root system in radial direction [s^{-1}]
$K_{r_i}^R$	Root hydraulic conductivity of i^{th} plant species in radial direction
$K_{r_i}^A$	Root hydraulic conductivity of i^{th} plant species in axial direction
LAD	Leaf area density [m^2/m^3] for 1-D, [m^2/m^4] for 2-D
$LAI_{combined}$	Sum of leaf area indexes of multiple species
$LAI_{mesquite}$	Leaf area index of mesquite
$LAI_{understory}$	Leaf area index of understory

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List of Abbreviation Continued

Symbol	Description [Units]
LE	Latent heat flux [W/m^2]
LE_{soil}	Latent heat flux of soil
MLCan	Multi-layer canopy-soil (model)
Ph	Photosynthetic flux [μmol/m^2/s]
PPT	Precipitation [mm]
SRM	Santa Rita Mesquite savanna site in Arizona
$w_{bare\ soil}$	Fraction of bare soil area
w_{plants}	Fraction of area covered with plants
θ	Soil moisture
ψ_{r_i}	Root water potential of i^{th} plant species
ψ_s	Soil water potential

CHAPTER 1. INTRODUCTION

Hydraulic redistribution (HR) is a phenomenon of water distributed from wet to dry soil layers through roots as a preferential path. [Burgess et al., 1998, 2000, 2001a; Hultine et al., 2003, 2004]. HR is passively driven by soil water potential gradients between shallow and deep soil layers. HR facilitates aboveground-belowground interactions that drive water and carbon dynamics and generates emergent spatial patterns of soil moisture and vegetation distribution. Previous studies have demonstrated that HR has an impact on plant water uptake, energy partitioning, nutrient cycling, and water partitioning between different species. HR is found in a wide variety of species across a range of climate regimes, including semiarid areas. HR occurs in all ecosystems but its manifestation is most pronounced in ecosystems with distinct dry season where enhanced water gradients generates HR. Semiarid areas, which occupy about 40% of land surface on earth, and provide home to about 2.5 billion people, have been identified among the most vulnerable systems to climate change with significant socioeconomic implications. Semiarid eco-hydrologic systems are examined to provide deep insights for dry regions, which will enable broader generalizations regarding the interaction between groundwater, vegetation roots and above ground dynamics and their role in whole-ecosystem performance.

Santa Rita Mesquite site in Arizona is a semiarid area and lies under North American Monsoon [Scott et al., 2008] with 50% of annual rainfall occurring during summer monsoon season. The site has distinct dry and wet season that provides preferential condition for HR occurrence. During the wet season, water moves from shallow layer to deep layer through roots and hydraulic descent (HD) occurs. During dry season, water moves from deep layer to shallow layer through roots and hydraulic lift (HL) occurs [Richards and Caldwell, 1987; Caldwell and Richards, 1989; Dawson, 1993, 1996; Caldwell et al., 1998; Schulze et al., 1998; Burgess et al.,

1998, 2000, 2001; Smith et al., 1999; Hultine et al 2003, 2004; Brooks et al., 2002, 2006; Scott et al., 2008; Neumann and Cardon, 2012; Cardon et al., 2013].

The eco-hydrological significance of HR has been demonstrated and accepted in the field of science. However, detailed integration of an experimental and eco-hydrological modeling has been lacking. In this study, the semiarid eco-hydrologic system is investigated through synthesis of modeling and experimental methods. Multi-layer canopy model (MLCan) is used to simulate HR on different plant species in semi-arid region and to examine the seasonality of HR fluxes and impact of HR on different species in the study site [Drewry et al., 2010a,b; Quijano et al., 2012; Le et al., 2011, 2012]. The model set up for the site, described in Chapter 3 (Section 3.3), is expected to reflect the seasonal change in plants and bare soil surface composition, and therefore capture aboveground and belowground linkages of water transport processes driven by HR in semiarid region. Soil moisture, energy flux, transpiration, photosynthetic flux, and HR flux are simulated with MLCan and compared with field measurements. The HR flux is studied in wet and dry season to capture seasonal interaction between aboveground and belowground water and to examine competitive and facilitative dependencies between co-existing plant species [Quijano et al., 2012]. Both measured and simulated results show that HD dominates in wet monsoon season and HL occurs between precipitation events, when water source from precipitation is absent. The way different plant species utilize water in different seasons indicates how plants adapted to use limited amount of water in semi-arid environment.

This thesis is organized as follows. Chapter 2 reviews published literatures to synthesize the knowledge related to hydraulic redistribution and introduce multi-layer canopy model framework developed for multispecies. Chapter 3 describes the study site and instrument installation in AZ and provides model setup for the Santa Rita Mesquite site. Chapter 4 provides the results from model simulation and discusses impact of different fraction of area covered by vegetation and soil and impact of hydraulic redistribution. Comparisons are made between results simulated with different root conductivity ratio between mesquite and understory. Last part of Chapter 4 concludes with a summary and implications of the study.

CHAPTER 2. LITERATURE REVIEW

The multi-layer canopy (MLCan) model for soil-root-plant continuum is used to simulate aboveground and belowground dynamics in Santa Rita Mesquite site with focus on HR. In this chapter, the published literatures on HR are reviewed in Section 2.1. The framework of the model that serves as a basic tool of this research is described in Section 2.2 with highlight on the need for developing the model suitable for horizontally heterogeneous area.

2.1. HYDRAULIC REDISTRIBUTION

Transport of water between plant roots and soil affects aboveground and belowground ecophysiological dynamics that involves nutrition, water and energy exchange. Uptake of water and nutrients is used by plants for metabolic activities and determines soil moisture distribution along the soil depth where plant roots can reach. Plant roots uptake water and nutrient for plant demand. However, the same process in the opposite direction, water released from the roots to soil, was detected in experiment conducted by Kramer [1993] and has been observed in different species across a wide range of climate zones. It has been observed in semiarid deserts [Ryel et al., 2002; Hultine et al., 2003], savannas [Ludwig et al., 2003], temperate [Emerman and Dawson, 1996], and tropical forests [Meinzer et al., 2004; Oliveira et al., 2005]. The process by which water distributed from wet to dry soil layers through roots as a preferential path across moisture gradient is called Hydraulic Redistribution (HR) [Burgess et al., 1998, 2000, 2001a; Hultine et al., 2003, 2004]. HR occurs as root hydraulic conductivity is significantly higher than surrounding soil hydraulic conductivity and, therefore, root transports moisture at higher rate than soil does. The mechanism of HR is shown in Figure 1. During the daytime plant uses water

for transpiration by opening stomata, which creates water potential gradient between plant leaves and plant roots. It creates water potential from the soil to plant roots and from plant roots to plant leaves. As a result, moisture in the soil layers is transported through plant roots and reaches plant leaves. The daytime HR occurs in the same direction both in wet and dry seasons. The contrast of HR direction between wet and dry seasons is observed during nighttime when stomata are closed. Without water demand form plant leaves, HR is governed by water gradient between plant roots and surrounding soil. During wet season, soil moisture in shallow layers increases with large amount of precipitation. Therefore, plant roots transport moisture into deeper soil layers since water potential in deep soil is lower than water potential in shallow soil. On the other hand, during dry season, shallow soil layers near the surface are drier than deeper soil layers and plant roots redistribute moisture upwards at nights. The directions of the water transport are observed along horizontal [Brooks et al.,2002], vertically downward [Burgess et al., 1998; Hultine et al., 2003], and vertically upward [Caldwell and Richards, 1989]. The phenomenon of moisture moving from shallow layer to deep layer through root is known as hydraulic descent (HD) and moisture moving from deep layer to shallow layer is known as hydraulic lift (HL) [Richards and Caldwell, 1987; Caldwell and Richards, 1989; Dawson, 1993, 1996; Caldwell et al., 1998; Schulze et al., 1998; Smith et al., 1999; Brooks et al., 2002, 2006; Scott et al., 2008; Neumann and Cardon, 2012; Cardon et al., 2013].

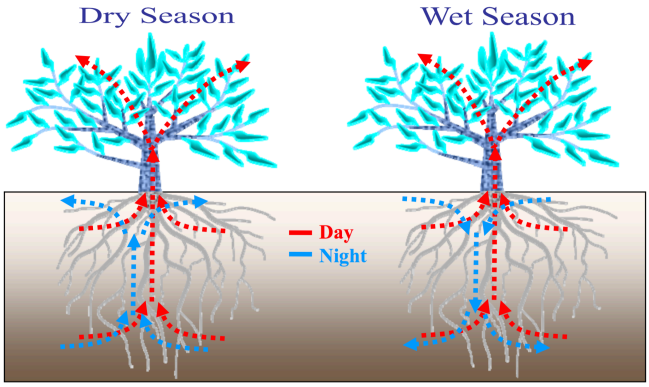

Figure 1: Mechanism of the hydraulic redistribution during dry and wet seasons [Amenu and Kumar, 2008]

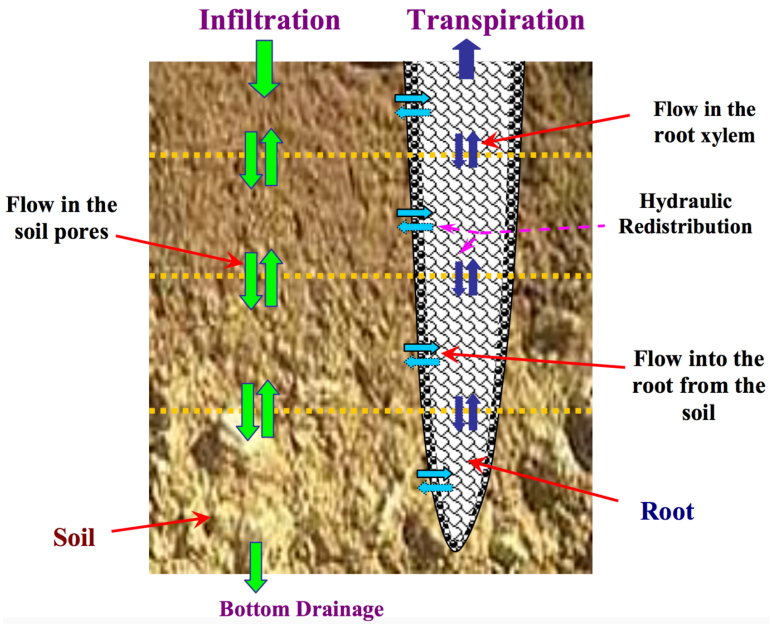

Figure 2: Direction of belowground water flow with hydraulic redistribution [Amenu and Kumar, 2008]

The implications of HR have an important impact on plant ecosystems. The benefit of HR are enhancing net productivity and plant transpiration [Amenu and Kumar, 2008; Scott et al., 2008; Quijano et al., 2012], buffering soil moisture loss in dry season [Bleby et al., 2010], extension of plants growing season [Ryel et al., 2002, Scott et al., 2008], nutrient acquisition and root litter decomposition [McCulley et al., 2004], increase in deep nutrients mobility [McCulley et al., 2004], and improvement in plant root health by homogenize soil moisture. Plants may allocate water to meet evaporation and transpiration demand. By HD, plants transport water to deep soil layers to avoid water loss by surface soil evaporation. By HL, plants may transport water to shallow soil layers to support transpiration.

Although the occurrence of HR is widely accepted, the magnitudes of HR fluxes remain highly uncertain since belowground measurements and experiments are rarely conducted. Also physiological variables related to HR, such as root hydraulic conductivities, contain high uncertainty. As a result, the result from Neumann and Cardon [2012] shows discrepancy in magnitude of HR fluxes between experimental data and modeled result. The experimental measurements showed 0.04 to 1.3 mm day^{-1} whereas the result from numerical simulation estimated HR flux as 0.1 to 3.23 mm day^{-1}. The possible source of discrepancy is plugging

wrong values as inputs of the numerical simulation. Another possible reason that experimental data is smaller than modeled result is missing period during HR flux measurements. There were temporal gaps in HR flux measurements. Despite of the discrepancy between the measured and modeled HR flux, an attempt to quantify HR is a meaningful approach. Quantified measures of HR by different plant species are published in literatures. *Quercus suber* (corkoak tree) transported water through their roots and the water is used to supply 17-81% of transpiration of the next day [Kurz-Besson et al., 2006]. *Acer saccharum* (sugar maple) transported 203 l of water through HL to support 25% of transpiration [Emerman and Dawson, 1996].

Most of the studies related to HR have been focusing on the net impact of HR on the transpiration and gross productivity of single species plant [Caldwell and Richards, 1989; Brooks et al., 2002; Ryel et al., 2002]. In Chapter 4 (Section 4.2.2), the study evaluates competitive or facilitative interaction between different plant species. The presence of co-existing plants may indicate competition for shared resources, such as soil, water and nutrients, the experimental result of multispecies system suggests that facilitative relationship between different species may exist [Scott et al., 2008]. The model described in the next section is capable of simulating the interaction between multispecies with incorporation of HR.

Precipitation is one of the main factors that impacts transpiration and HR fluxes since precipitation provides the main source of water that is redistributed by tree roots. To examine how different amount of precipitation impacts HR, sensitivity of HR is numerically analyzed with different mean annual precipitation. Quijano used ten years of data for model simulation in Tapajós site, one of the Ameriflux site. For simplification in comparison, LAI and other physiological factors are kept constant and only the amount of mean annual precipitation is altered. In water-limited environment, where precipitation governs plant transpiration, increase in precipitation results in higher transpiration. However, in energy-limited environment, where available water does not control transpiration, transpiration does not response to increased precipitation. The modeled simulation done by Quijano shows that maximum HR occurs with certain range of mean annual precipitation. HR flux reduces with both low and high precipitation. Small amount of precipitation results in low soil moisture and low soil hydraulic conductivity that leads to reduction in HR flux. On the other hand, large amount of precipitation provides abundant water throughout all soil depths and reduces soil water potential gradient, which also leads to reduction in HR flux.

Another main factor that has a significant impact on ecohydrological dynamics is root hydraulic conductivity that determines the rate of water transport from soil to plants. Root hydraulic conductivity can act as a limiting factor of transpiration and HR fluxes. The impact of root hydraulic conductivity on HR and transpiration is studied by analyzing the sensitivities of HR and transpiration in Quijano et al. [2015]. Reduction of root hydraulic conductivity decreases both HR and transpiration but the HR flux shows more significant decrease. Even with one magnitude reduction in radial root hydraulic conductivity, from 10^{-7} to 10^{-8} m $MPa^{-1}s^{-1}$, the resulting transpiration shows no response. With increasing radial root hydraulic conductivity, transpiration increases until it reaches the maximum threshold. Once it reaches the threshold, the limiting factor of transpiration switches from water to energy or other physiological factors. On the other hand, increasing axial root hydraulic conductivity appears to have no upper threshold and always results in increased HR. In Chapter 4 (Section 4.2.3), we examine how different ratio of root hydraulic conductivities of multiple co-existing species impacts each species.

2.2. MULTI-LAYER CANOPY MODEL

The multi-layer canopy (MLCan) model for soil-root-plant continuum is a 1-D eco-hydrological model, which is used to simulate aboveground and belowground linkages [Drewry et al., 2010a,b; Quijano et al., 2012; Le et al., 2011, 2012]. MLCan couples leaf-level eco-physiologic processes with physical processes and belowground water to incorporate photosynthesis, stomatal conductance, energy balance and boundary layer conductance. The model resolves the shortwave and longwave radiation regimes through multi-layers of canopy by leaf area density profile [Drewry et al., 2010a]. The model takes inputs such as shortwave radiation (R_g), longwave radiation (R_{lw}), wind speed (U), atmospheric temperature (T_a), atmospheric vapor pressure (e_a), and precipitation (ppt) and generates latent heat, sensible heat and CO_2 fluxes for different canopy layers as a solution of leaf energy balance. Based on the vertical leaf area density structure, forcing variables are turned into vertical profile. Canopy model solution starts with solving radiation regimes. Direct shortwave radiation at the top of the canopy is calculated according to Beer's law and diffused shortwave radiation is calculated between canopy layers until convergence. Longwave radiation is also calculated through

iteration until convergence. The residual radiation after shortwave and longwave calculation is set to reach soil surface directly. After solving for radiation, Energy and water fluxes for soil are calculated. For soil moisture, Richards' equation is used and vertical soil moisture profile is calculated at each time step for hydraulic redistribution. For leaf photosynthesis, Farquhar equation is used [Farquhar et al., 1980] and for stomatal conductance, Ball-Berry equation is used [Ball et al., 1987]. Leaf energy balance is calculated using Nikolov et al. [1995] and soil energy balance is determined using the numerical solution as provided in Oleson et al. [2004]. The model is capable of simulating facilitative and competitive interaction between multispecies with shared resource dynamics. Different plant species co-exist in the ecosystem and interact with other species in aboveground (radiation attenuation, energy partitioning and photosynthetic productivity) and belowground (water and nutrient uptake) processes (Figure 3).

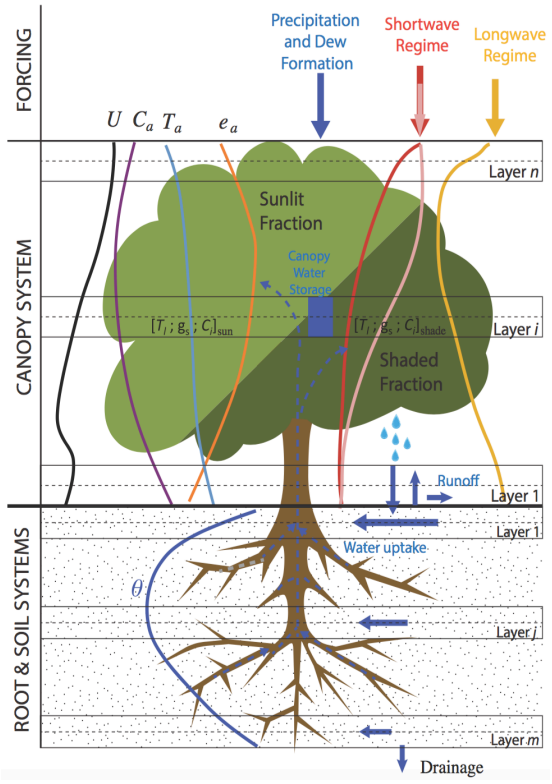

Figure 3: Aboveground and belowground linkages coupled in Multi-layer canopy model [Drewry, 2010]

The current version of the model is capable of simulating multispecies plants including plants with C3 and C4 photosynthetic pathways. The interaction between co-existing species is coupled by using shared resource model where the soil acts as a common reservoir allowing root access of multiple plants. The model is set up based on Amenu and Kumar [2008] for root and soil interaction of single species. The model is developed based on Drewry et al. [2010 a,b] for multispecies composition for both C3 and C4 plants and the coupling of aboveground and belowground water and energy dynamics. The details of MLCan development can be found in previous literatures [Drewry et al., 2010a; Quijano et al., 2012].

The model is capable of modeling the feedback between different plant species, which share resources, such as soil, water and nutrients. Using the model, it is possible to get quantified measure of water fluxes attributed to each species. There are aboveground and belowground dynamics considered in multispecies system. For aboveground process, the model uses the structure of multispecies to solve for partitioning of the solar radiation regime and water uptake pattern. For leaf area density (LAD) calculation, LAD of each species is summed as a compound LAD, which determine radiation regime through vertical profile of co-existing plant species and the residual radiation reaching the soil surface. Then the energy is partitioned to different plant species according to the fraction of LAD of particular species to compound LAD. For belowground process, roots of different species release and uptake water simultaneously from a shared resource pool. It allows examining competitive and facilitative relationship between multispecies. The framework of the multispecies model described in this paragraph is visually presented in the figure 4.

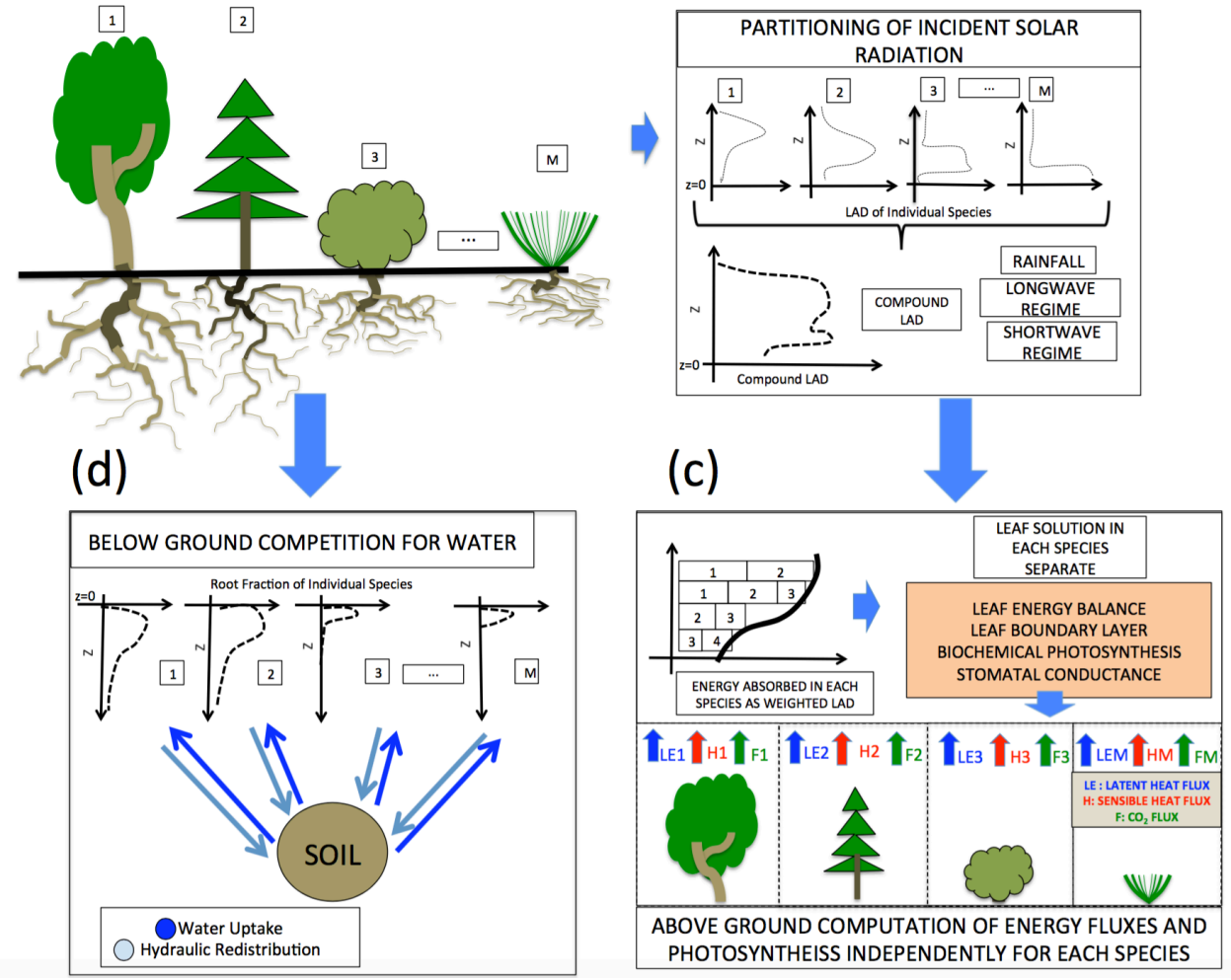

Figure 4: Framework of the multispecies MLCan model [Quijano et al., 2012]

For belowground water transport, equation for HR is developed to simulate root-soil dynamics in the ecosystem [Mendel et al., 2002]. For multispecies system, multiple plants species with different rooting depth and root structure access to different depth in soil layers and indirectly interact by sharing resources. The coupling between root and soil is solved for all plant species simultaneously. The model simulates water flow through roots with steady state approximation coupled with unsteady Richards Equation, an equation commonly used to examine water flow in soil [Amenu and Kumar 2008; Quijano et al., 2012]. The equations used for belowground soil moisture are provided below. HR flux occurs from plant root to the surrounding soil when root water potential (ψ_r) becomes higher than soil water potential (ψ_s).

For cases where HR is suppressed, radial root hydraulic conductivity is set equal to zero when root water potential is higher than soil water potential.

$$\frac{\partial \theta}{\partial t} - \frac{\partial}{\partial z}\left[K_s\left(\frac{\partial \psi_s}{\partial z} - 1\right)\right] = -\sum_{i=1}^{M} K_{r_i}^{R}\left(\psi_s - \psi_{r_i}\right)$$

$$-\frac{\partial}{\partial z}\left[K_{r_1}^{A}\left(\frac{\partial \psi_{r_1}}{\partial z} - 1\right)\right] = K_{r_1}^{R}\left(\psi_s - \psi_{r_1}\right)$$

$$-\frac{\partial}{\partial z}\left[K_{r_2}^{A}\left(\frac{\partial \psi_{r_1}}{\partial z} - 1\right)\right] = K_{r_2}^{R}\left(\psi_s - \psi_{r_2}\right)$$

$$\vdots$$

$$-\frac{\partial}{\partial z}\left[K_{r_M}^{A}\left(\frac{\partial \psi_{r_M}}{\partial z} - 1\right)\right] = K_{r_M}^{R}\left(\psi_s - \psi_{r_M}\right)$$

In the equation, M is number of plant species, ψ_s is water potential in the soil and ψ_r. is water potential in the roots of i^{th} plant species. The term θ represents soil moisture and z represents vertical coordinate and t represents time step. The term K_s is hydraulic conductivity of soil, and $K_{r_i}^{R}$ and $K_{r_i}^{A}$ represents radial and axial root conductivities of i^{th} plant species. Since multiple species access the common soil resource, soil moisture (θ) and soil water potential (ψ_s) are the same for all co-existing plant species. Since multiple species are indirectly related through shared resource, a water release from one plant species may benefit another plant species that share the same soil layer.

One of the main factors that determines HR is plant root biomass distribution in vertical direction. Root biomass distribution is a unique characteristic related to plant species and climate zone. In the model, root biomass distribution is generated based on Schenk and Jackson paper [2002], as presented in equation below. Parameters for calculating vertical root distributions in the soil profile are extracted from published literatures [Schenk et al., 2002].

$$F_{root}(z) = \left[\frac{1}{1 + \left(\frac{z}{z_{50}}\right)^{c}}\right]$$

In the equation, $F_{root}(z)$ represents the cumulative fraction of root biomass above a depth of z, z_{50} is the depth where half of cumulative root biomass is located, and z_{95} is the depth where 95% of cumulative root biomass is located. The term c is a dimensionless parameter determined by z_{50} and z_{95}. Values of MLCan parameters, including z_{50} and z_{95}, are presented in Chapter 3 (Section 3.3).

The model includes hydraulic fuse mechanism which allows hydraulic disconnection between plants root and surrounding soil if the soil water potential is less than the wilting point to prevent water uptake and water release by the roots. It reflects plant roots mechanism of reducing water flux in water-limited environment by shrinkage or death of fine roots in shallow depth soil near the surface.

The MLCan version used in this study is 1-D version that is capable of simulating only in vertical direction. Since the dimension is limited in one direction, the input and output variables of the model are representative of the domain of horizontal area with an assumption that plants are distributed homogeneously in the area. 1-D version of MLCan is not capable of treating areas that are not homogeneous in spatial domain, where some area is covered with plants and some area is exposed as bare soil. In such cases, area covered with plants and area exposed as bare soil are treated separately and combined later using the ratio of two areas. In Chapter 3, model framework for simulating horizontally heterogeneous area is provided.

Santa Rita Mesquite site is water-limited environment with distinct dry season. During dry periods, plants redistribute water to deep layer soil through mesquite roots to avoid water loss to surface evaporation. In water-limited environment, the magnitude of soil evaporation largely impacts the water cycle. Soil evaporation is reduced with the presence of a litter on the surface since it serves as a protection from the direct radiation, reducing the moisture demand in the atmosphere. In the study site, a litter layer is formed when the understory plant dies during the winter. Their photosynthetic mechanism is shut down but their dead leaves attenuate the radiation and reduce direct radiation to the soil. The presence of a litter layer on the surface increases available soil moisture in shallow depth, reduces soil water potential gradient and

affects HR fluxes [Quijano et al., 2012]. For the simulation of Santa Rita Mesquite site, a litter layer of 3 cm over the soil surface is included.

For detailed description of the model development refer to Amenu and Kumar [2008] and for framework of multispecies extension, refer to Quijano et al. [2012].

CHAPTER 3. SITE DESCRIPTION AND MODEL SETUP

The description of HR and the framework of the MLCan are described in the previous chapter. In this study, HR process is analyzed by multi-layer canopy model (MLCan) to examine the effect of HR on different plant species. Therefore, the description of the study site and the research method is presented in this chapter. The Santa Rita Mesquite savanna site is described in Section 3.1 and field measurement methods are explained in Section 3.2. The development of 1-D model setup for horizontally heterogeneous area is discussed in Section 3.3.

3.1. SITE DESCRIPTION

The study site is one of Ameriflux sites: Santa Rita Mesquite savanna (SRM). The Santa Rita Mesquite savanna site is located on the Santa Rita Experimental Range (SRER) in southern Arizona (31.8214°N, 110.8661°W, elevation 1116m). It is a semi-arid savanna with an ecosystem that lacks access to stable ground water source. The soil texture is uniform in all depths with sandy loam. The site lies in subtropical climate zone and has a summer monsoon season and distinct dry season, which indicates the occurrence of HR. Mean annual precipitation (2004-2012) is 377mm and around 50% of the annual rainfall occurs during the North American monsoon (July-September). Since summer monsoon is the main water source throughout a year, studying before and after monsoon shows how ecosystem responses to climatic variability.

The site has changed from semi-desert grassland into savanna due to the encroachment of the woody leguminous tree, *Prosopis velutina* woot (velvet mesquite) [Glendening, 1952; McClaran, 2003]. Now, the vegetation of the site consists of Velvet Mesquite and understory bunchgrass that co-exist and share resources. Average leaf area index (LI-2000, LI-COR, Inc.,

Lincoln, NE) of the mesquite is 0.22-0.41 and average height is 2.5m (SD=1.6, n=95). Mesquite has a deep taproot and wide-ranging lateral roots [Cable, 1977], which is suitable to redistribute belowground water from different soil layers over area reached with lateral roots [Scott et al., 2008]. Total mesquite cover was about 35%, understory cover was about 15% with 7% of them growing under mesquite canopy. Growth of mesquite and understory peaks during summer monsoon when the major water source is available. During dry season, areas of plants cover decreases and patches of bare soil (57%) are formed between plants.

The study site is suitable for HR examination because it has a published record of HR process with pronounced dry season and has field data available. The evidence of HR occurring in Santa Rita Mesquite site is published in previous literatures [Scott et al., 2008]. Large amount of water is distributed through mesquite roots and the process is observed even during the canopy dormant season [Hultine et al., 2004]. During the dormant season, lateral roots of the mesquite uptake precipitation from shallow soil depth and redistribute to deep lateral roots and tap roots. Mesquite roots stores water to the deep soil layer to keep water from soil evaporation. Stored water by mesquite roots may benefit plants later during dry season and extend the growing season by providing stored water in the absence of precipitation. HD also occurs while the mesquite is active and water is abundant in shallow soil layers. As the soil near surface gets dry, mesquite uses water in deep soil depth to meet the water demand of evaporation and transpiration. Scott et al. [2008] implied that mesquite stores water through HD to transpire more in the following spring based on the relationship between mesquite sap flow and above-canopy fluxes. At the study site, HR process is detected, but the implications of HR on overstory-understory interactions and resulting spatial patterns and gradients remain untested.

3.2. INSTRUMENTATION AND MEASUREMENTS

In Santa Rita Mesquite site, field measurements, including data monitored by Ameriflux tower, are collected. Data measured by Ameriflux tower using the eddy covariance technique includes water flux, energy flux, and carbon dioxide flux. At 8 m height, an open-path infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, NE) and sonic anemometer (Model CSAT-3; Campbell Scientific Inc., Logan UT) were installed to measure wind velocity, concentration of

water vapor and concentration of carbon dioxide in 30 minutes interval [Scott et al., 2009]. We used the measured data as atmospheric forcing of MLCan model and used energy fluxes as validation of the model result.

In Figure 5, incoming shortwave, precipitation, and LAIs of mesquite and understory that are later used for HR examination are plotted. Precipitation and shortwave radiation are two main factors that affect soil water potential and HR flux. The seasonality of precipitation determines wet and dry periods throughout the year. Seasonality of precipitation and shortwave generates temporal soil water potential gradient and variation in HR fluxes.

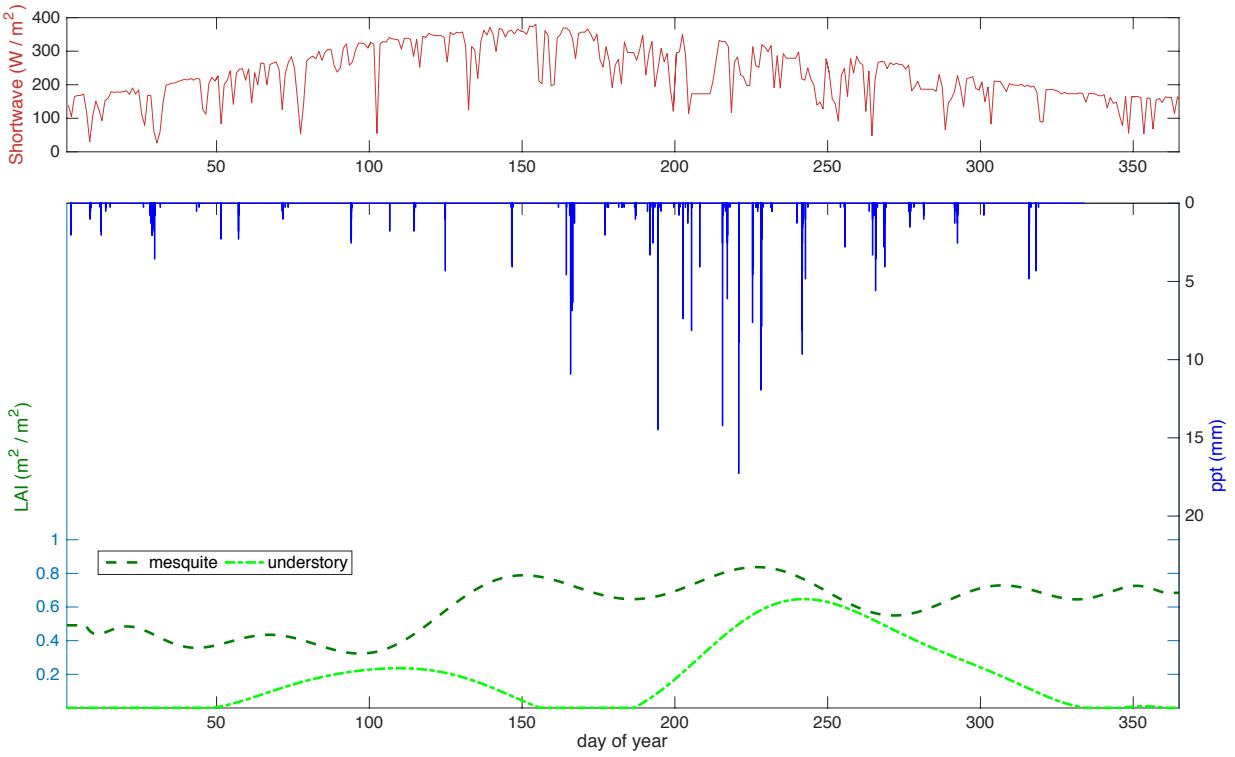

Figure 5: Climatological data from Santa Rita Mesquite site used for model simulation (top) Daily average of downward shortwave radiation of year 2015, (middle) Precipitation of year 2015, (bottom) leaf area index (LAI) of mesquite and understory

Also soil moisture and soil temperature data through the soil profile are available for the site. With soil moisture probes (CS616-L, Campbell Scientific, Logan, UT), volumetric soil

content was measured in 30 minutes interval. We monitored soil moisture at 5, 10, 20, 30, 50, 70, 100, and 130 cm depth. The soil texture in the site is uniform in all depths with sandy loam and the soil moisture varied with water potential gradients. Since soil moisture is monitored in one spot of a large study site, the soil moisture probe measurement cannot represent the soil moisture of the study site, but it serves as a sample measurement.

To examine HR by mesquite roots, we used heat ratio method to measure sap flux, an indicator of HR flux, in lateral roots, taproot, and trunk of trees. Measurement of sap flux is a suitable approach since mesquites are ring porous and water transports through stem xylem in the outer tree ring [Scott et al., 2008]**.** To study the impact of HR, five trees are chosen as treatment trees. For treatment trees, lateral roots are cut to server HR process that impacts both mesquite and understory plants. One of the five treatment trees is chosen and sap flux measurement is installed at the tree trunk and taproot. For three control trees (trees that lateral roots are not cut), we monitored sap flux at trunk, taproot, and lateral roots. The map of Santa Rita Mesquite site and the location eddy covariance tower and the trees are shown in Figure 6. We excavated soil around roots and installed temperature probes at up- and downstream of a pulsed heat source to measure heat transferred up- and downstream, which is converted to sap flux [Burgess et al., 2001a, 2001b]. After sap flux measurement probes are installed, excavated area was covered with plywood to protect exposed roots from daytime direct sunlight and nighttime freezing. Sap flux is monitored in 30 minutes interval from May 2015 to May 2016.

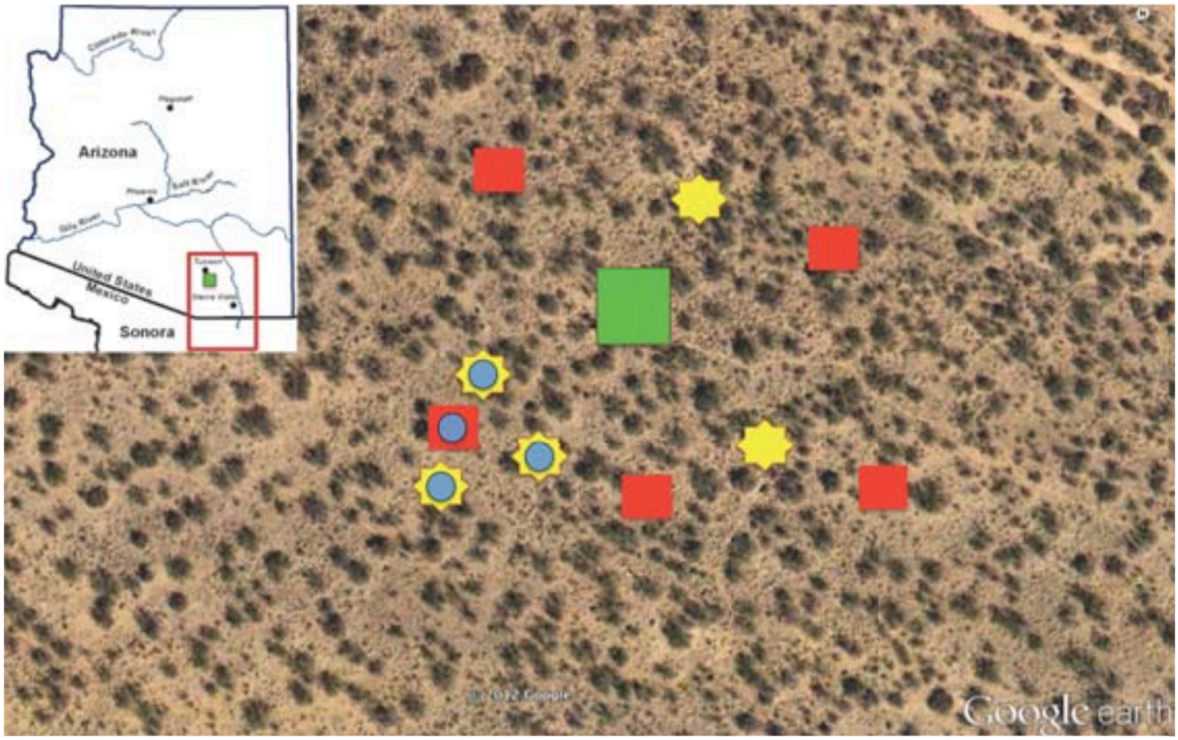

Figure 6: Google Earth image of Santa Rita Mesquite site. Green square shows the location of Santa Rita Mesquite eddy covariance tower. Five red squares represent five mesquites receiving the trenching treatment (mesquites without HR) and five yellow stars represent un-trenched mesquite (mesquites with HR). Four blue circles represent four mesquites with sap flux monitors at trunk, taproot, and lateral roots.

3.3. MODEL SETUP

The objective of this study is to study the impact of HR in the interaction between aboveground and belowground echohydrologic system in Santa Rita Mesquite site. In this section, we introduce how the framework of MLCan model, described in Chapter 2 (Section 2.2), is modified for Santa Rita Mesquite site simulation. Parameters used in MLCan simulation for Santa Rita Mesquite site are presented in Table 1. The fraction of plants and bare soil in the study site shows seasonal variation as shown in figure 7. The plants growth peaks during summer monsoon season, when rainfall is available as a major water source. The seasonal fluctuation of plants and bare soil area is incorporated in the model for a better representation of the site.

The composition of plants and bare soil is largely common in natural ecosystems. Throughout the year, plants grow and die and after the plant death, the area remains as bare soil until a growth of other plants. However, such natural seasonal phenomenon is not reflected in 1-D model. In 1-D model, the model is not capable of simulating co-existing areas covered with plants and bare soil. To incorporate the composition of areas covered with plants and bare soil, the result of two separate cases are combined as a weighted average according to the composited area.

For calculations of plants fraction and bare soil fraction, we calculate combined LAI by summing LAI of mesquite and LAI of understory. We assume that plants fraction is proportional to the sum of leaf area indexes of co-existing plants. The underlying assumption is that the overlapping area of mesquite and understory is negligible and when combined LAI reaches its maximum, the area is fully covered by plants and fraction of bare soil surface coverage becomes zero. Then we calculate weight of plants area by dividing combined LAI by the maximum value of combined LAI in each time step. Since the sum of weights of plants area and bare soil area equals to 1, we calculate weight of bare soil area by subtracting weight of plants area from 1. In Santa Rita Mesquite site with two plant species, we calculate plants fraction following equation.

$$LAI_{combined} = LAI_{mesquite} + LAI_{understory}$$

$$w_{plants} = LAI_{combined} / \max(LAI_{combined})$$

$$w_{bare\ soil} = 1 - w_{plants}$$

In this section, the framework of MLCan model incorporating seasonality of bare soil and plants is described. Including bare soil fraction affects both aboveground (radiation regimes, soil evaporation and energy balance) and underground (soil moisture distribution and soil water potential gradient) dynamics. Bare soil is exposed to direct radiation without attenuation of radiation energy. Therefore, incorporating bare soil fraction in the model increases ground heat (G) and latent heat (LE_{soil}) from soil and decreases sensible heat (H).

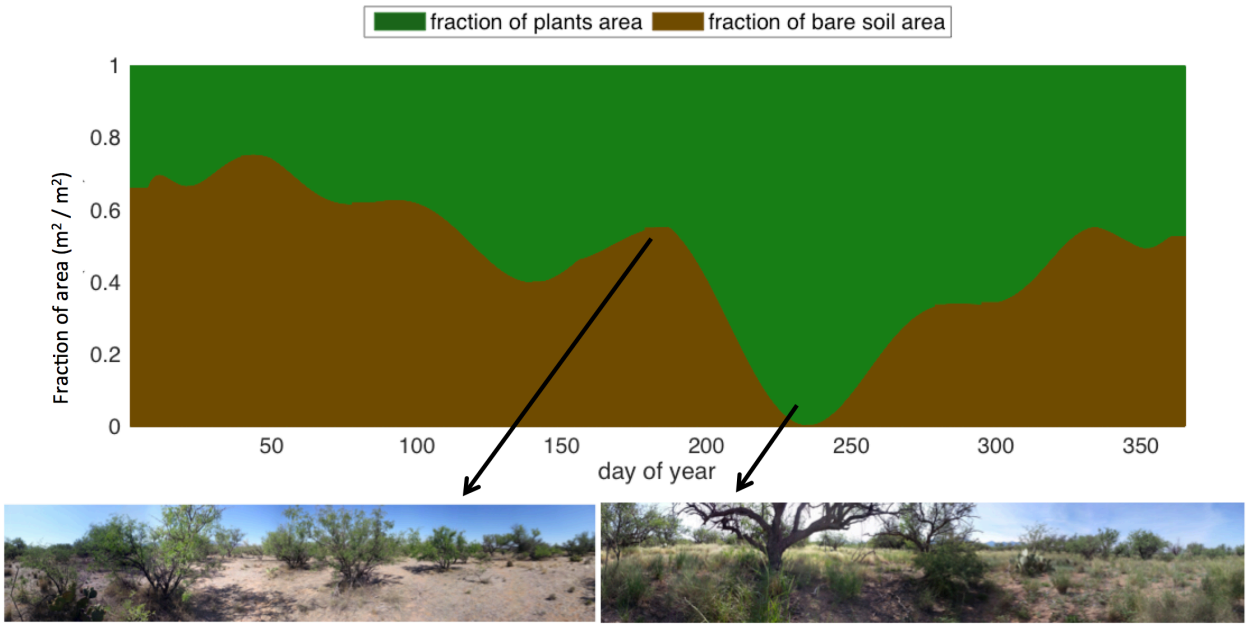

Figure 7: (top) Fraction of plants area and bare soil area throughout a year, (bottom left) Pictures of Santa Rita Mesquite site taken on June 18th (doy of 169) and (bottom right) on August 17th (doy of 229)

To obtain MLCan result that combines areas with plants and areas with bare soil, we calculate the weighted average of MLCan result for plants and MLCan result for bare soil. The assumption of the calculation is that mesquite does not affect radiation regime of neighboring mesquites. The assumption seems to be valid since the mean height of mesquite, 2.5 m, is relatively short and mesquites are located far apart as shown in pictures in Figure 7.

$$\text{MLCan result}_{\text{combined}} = (w_{plants})(\text{ MLCan result}_{\text{plants}}) + (w_{bare\ soil})(\text{ MLCan result}_{\text{bare soil}})$$

Table 1: List of parameters used in the simulation for Santa Rita Mesquite site

Description	Symbol	Mesquite	Understory	Units
	Photosynthesis			
Maximum rate of Rubisco carboxylation at 25°C	$V_{c\,max}$	17.62	39	µmol / m^2s
Maximum electron transport rate	J_{max}	13.55		µmol / m^2s
Leaf respiration	Rd_{25}	0.166		µmol / m^2s
	Conductance and Leaf physiology			
Ball Berry slope	m	9	12	mol/m^2s
Ball Berry intercept	b	0.01	0.008	MPa
Leaf potential at which half of the hydraulic conductance is lost		-3		
	Leaf and Canopy			
Leaf width (Needle diameter)	d_o	0.0312		m
Canopy height	h_c	2.5		m
Flux tower observation height	h_t	7.82		m
	Soil property			
Percent of sand		75		%
Percent of clay		10		%
	Root Structure			
Maximum Root depth	r_d	0.75		m
Fiftieth percentile rooting depth	z_{50}	0.28	0.24	m
Ninety-fifth percentile rooting depth	z_{95}	1.5	0.65	m
	Litter Layer			
Litter layer depth		0.03		m

CHAPTER 4. RESULTS AND DISCUSSION

In this chapter, we examine the impact of seasonality and HR on ecosystem and coupled water dynamics. Using MLCan model that incorporates composition of plants and bare soil, we simulate ecophysiologic dynamics in Santa Rita site and compare with field measurements of soil moisture and energy fluxes in Section 4.1.1. Water uptake and HR by plant roots plays an important role in hydrologic cycle. Plants uptake water from soil to use for transpiration during daytime and release water to soil to transport water to different soil depth. The seasonality of HR is presented in Section 4.1.2 and the impact of HR on water dynamics and the interaction between mesquite and understory is illustrated in Section 4.2.

4.1. SEASONAL IMPACT

Simulated result from incorporating seasonal fluctuation of plants fraction and bare soil fraction is compared with simulated result of plants in Section 4.1.1. We compare the combined MLCan result of plants and bare soil with measured data by plotting their soil moisture in different depths and energy fluxes.

The uptake of soil moisture for plants transpiration is driven by different variables such as leaf phenology, distribution of root and soil moisture. In multi species system, soil moisture distribution is mainly developed by soil water uptake/release of different plants. Different characteristics of multispecies lead to complex coupled system allowing competitive and facilitative interactions. In Section 4.1.2, we plot water release/uptake in different depths simulated by the model to evaluate the seasonal impact of HR on different species.

4.1.1. Seasonality of Plants and Bare Soil Composition

In this section, the result from MLCan simulation with bare soil and plants composition framework described in Section 3.3 is examined. The result presented in Figure 8 suggests that the dynamics of the multispecies composition are represented better through incorporation of plants and bare soil composition that varies from season to season. Since plants and bare soil fraction fluctuates through different seasons, we combined simulated result for plants and bare soil with regards to the fluctuation. Throughout the year in all soil depths, simulated result of bare soil shows higher soil moisture than simulated result of plants and measured data. Higher soil moisture in bare soil simulation may be due to absence of plants that uptake moisture to use for transpiration. In soil layer depths deeper than 10cm, simulated result of plants shows lower soil moisture than measured data. Combining the simulated results of plants and bare soil provides improved match between measured data and simulated result and gives the best representation of the site with seasonally varying plants and bare soil composition.

In figure 9, fluxes of ground heat, sensible heat, and latent heat are plotted for simulated result and field data. MLCan simulation that combines bare soil and plants gives a precise match with measured data for ground heat and latent heat fluxes. However MLCan simulation underestimates sensible heat, especially in dry season (doy from 1 to 200).

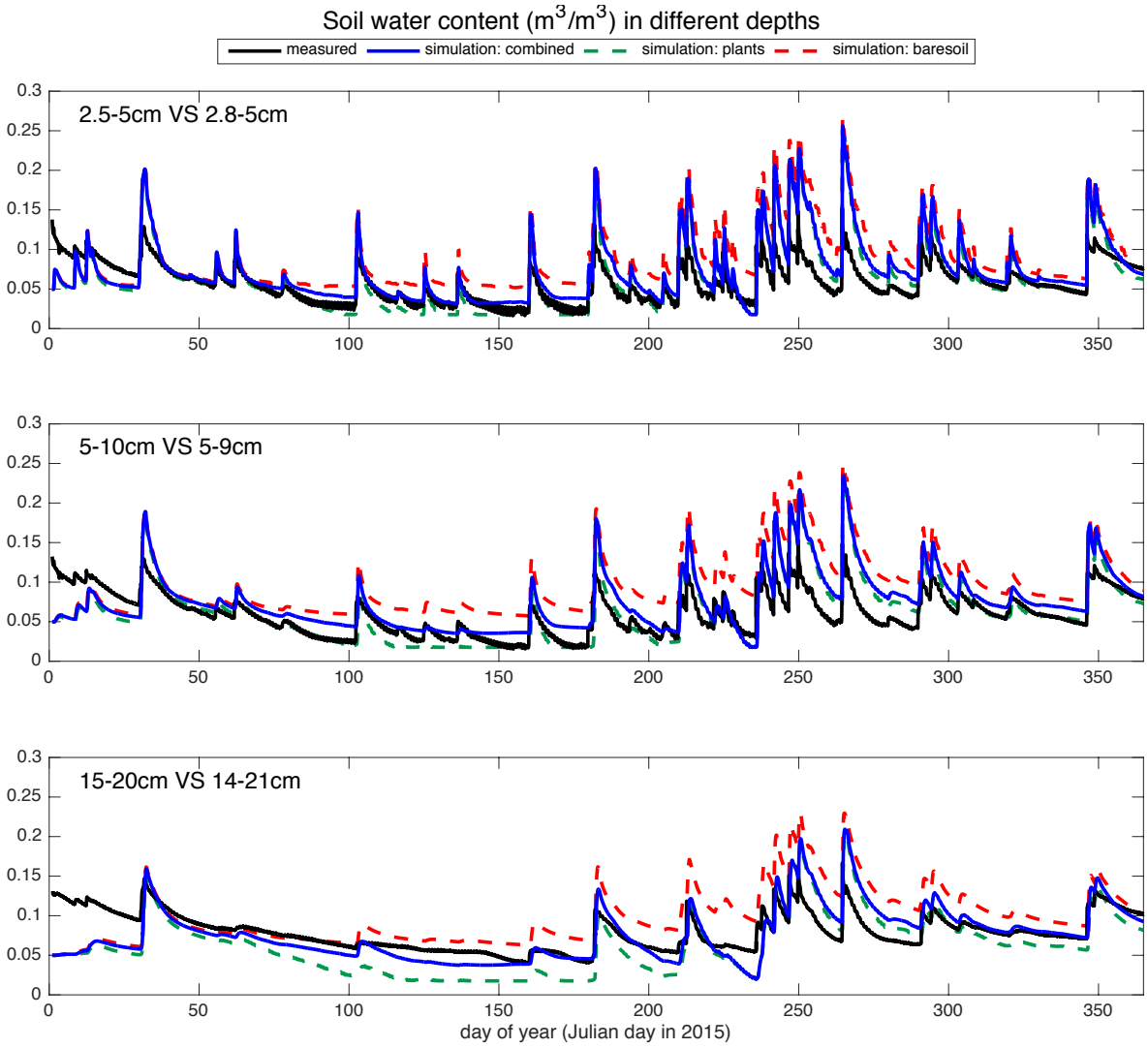

Figure 8: Soil moisture in different depth of model result vs. field measurement [2015 data]. Black solid line represents measured soil moisture, blue solid line represents model simulation of plants+bare soil combined soil moisture, green dotted line represents model simulation with plants, and red dotted line represents model simulation with bare soil

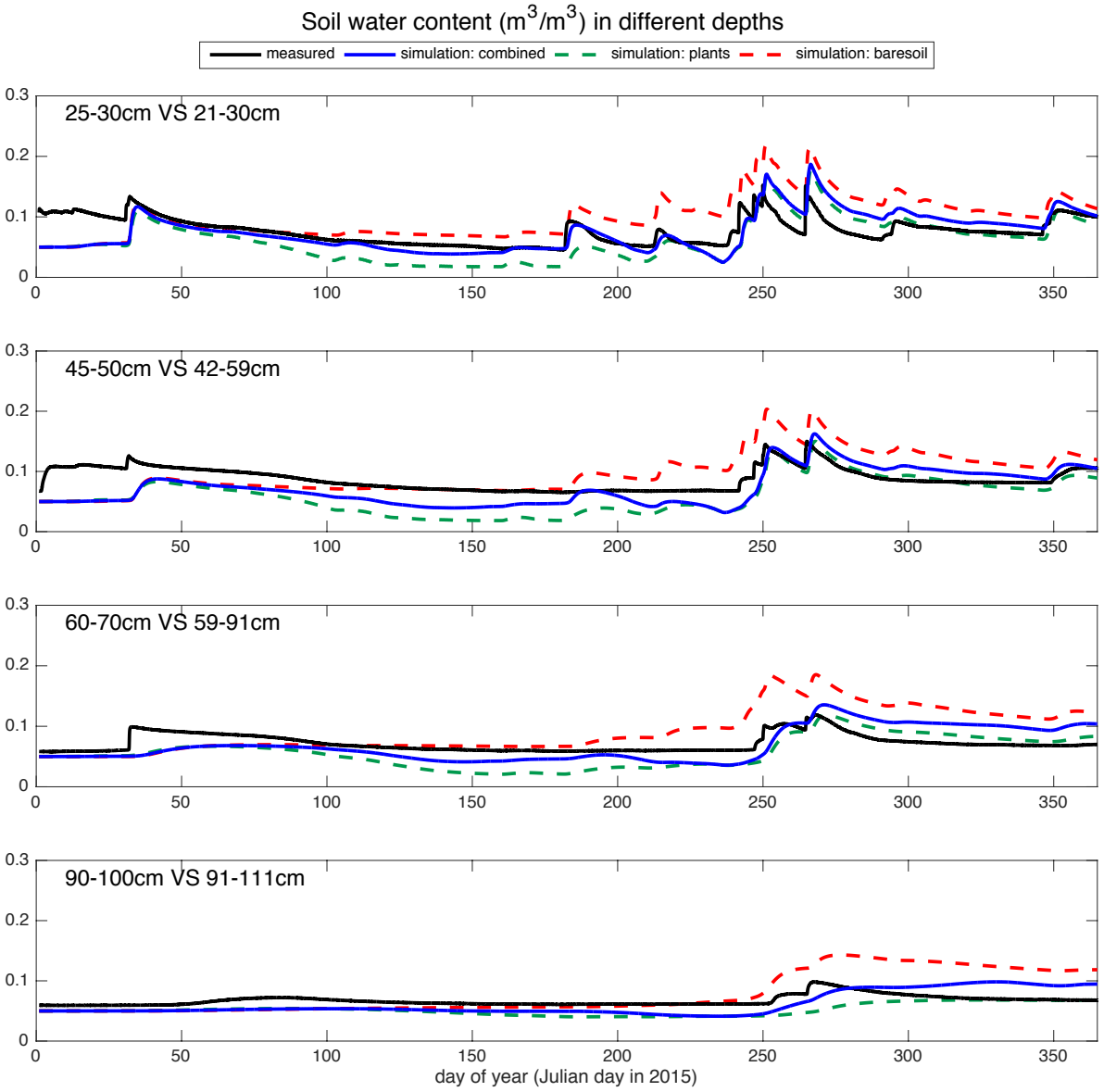

Figure 8 (cont.)

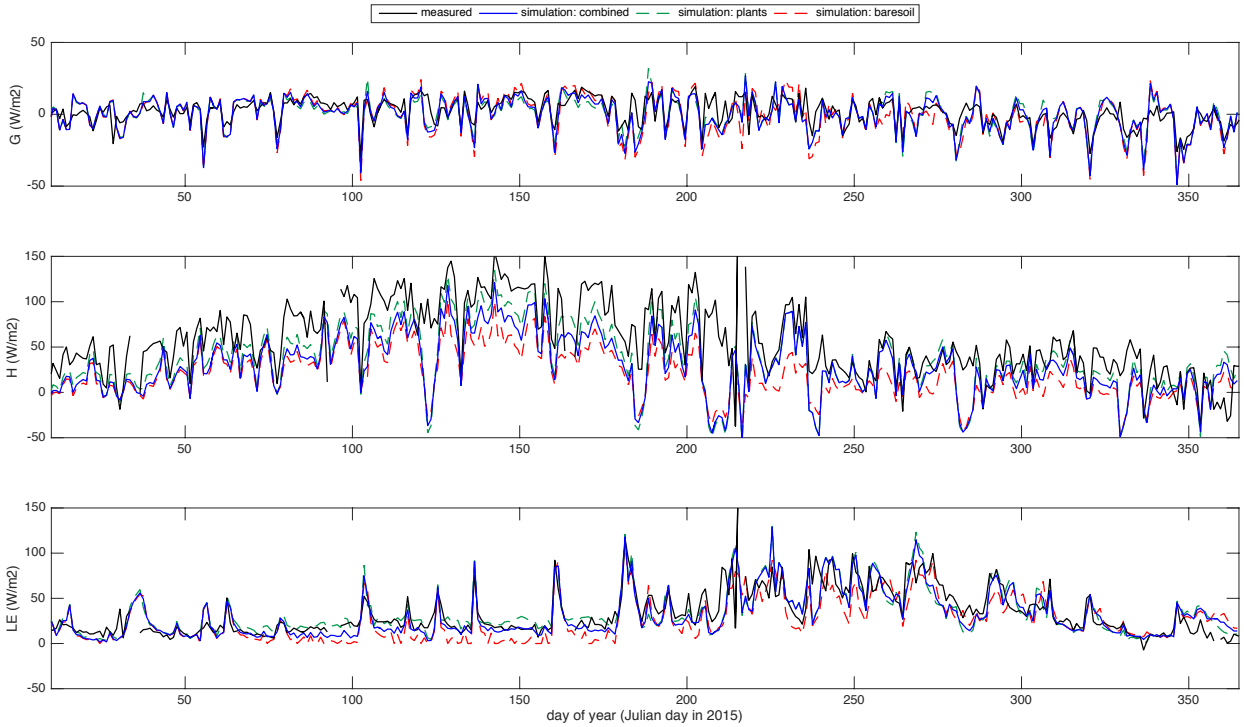

Figure 9: Energy flux (G, H, LE) of model result vs. field measurement [2015 data]. Black solid line represents measured energy fluxes, blue solid line represents model simulation of plants+bare soil combined energy fluxes, green dotted line represents model simulation with plants, and red dotted line represents model simulation with bare soil

4.1.2. Seasonality of Hydraulic Redistribution

In this section, we focus on how HR varies from dry season to wet season and how HR is classified into HL and HD. HR regulates belowground water fluxes through release and uptake of soil moisture. Figure 10 and 11 illustrate HR response to precipitation pulse in 10 days window of dry season and wet season, respectively. Figure 10 illustrates HL in dry season (around doy of 80) when water is transported to shallow layer with absence of precipitation. Figure 11 illustrates that precipitation (on doy of 221) switches the water transport from HL to HD. Based on the direction of water transport, we identified water uptake and release: water

moving from soil to root is absorption and water moving from roots to soil is release. If water is absorbed by roots in deep layer and released in shallow layer, we classified it as HL and if water is absorbed in shallow layer and released in deep layer, we classified it as HD. This classification of HR into HL and HD is done based on half hour data of root water uptake and release. Figure 12 shows measured sap fluxes and simulated HR fluxes (from May 2015 to December 2015) classified into HL and HD. Overall, the period and pattern of HR from simulated result aligned with sap flow measurement at mesquite taproot. As we hypothesized for systems without deep soil water storage, we found that HL occurs more episodic and HD dominates throughout the year. HD occurs immediately after storms, moving water to deeper soil layers to keep it from evaporation. However HD may reduce water availability for shallow-rooted understory. Significant HD during summer monsoon suggests that HR may extend the growing season of mesquites when surface soil dries after the monsoon, thus supporting transpiration through seasonal drought. On the other hand, HD may take away water from understory plants. HL occurs between precipitation events when water supply from precipitation is absent and it may increase water availability in shallow layer. Understory plants may benefit from water resources supplied by deep-rooted trees and survive dry period.

The main factors that determine seasonality of HR are incoming shortwave and precipitation because they determine soil moisture and water potential gradients. For reference, precipitation is plotted in Figure 10, 11, 12 and shortwave radiation is plotted in Figure 5 in Chapter 3 (Section 3.2). Seasonality of incoming shortwave generates seasonality of transpiration demand. High amount of shortwave demands more transpiration from plants, and therefore generates larger HR fluxes. Seasonality of precipitation determines the amount and direction of water transported through HR. During prolonged dry period, water potential gradients in soil are enhanced and HR flux increases. During period of continuous and uniform rainfall, potential gradients are reduced and HR flux decreases.

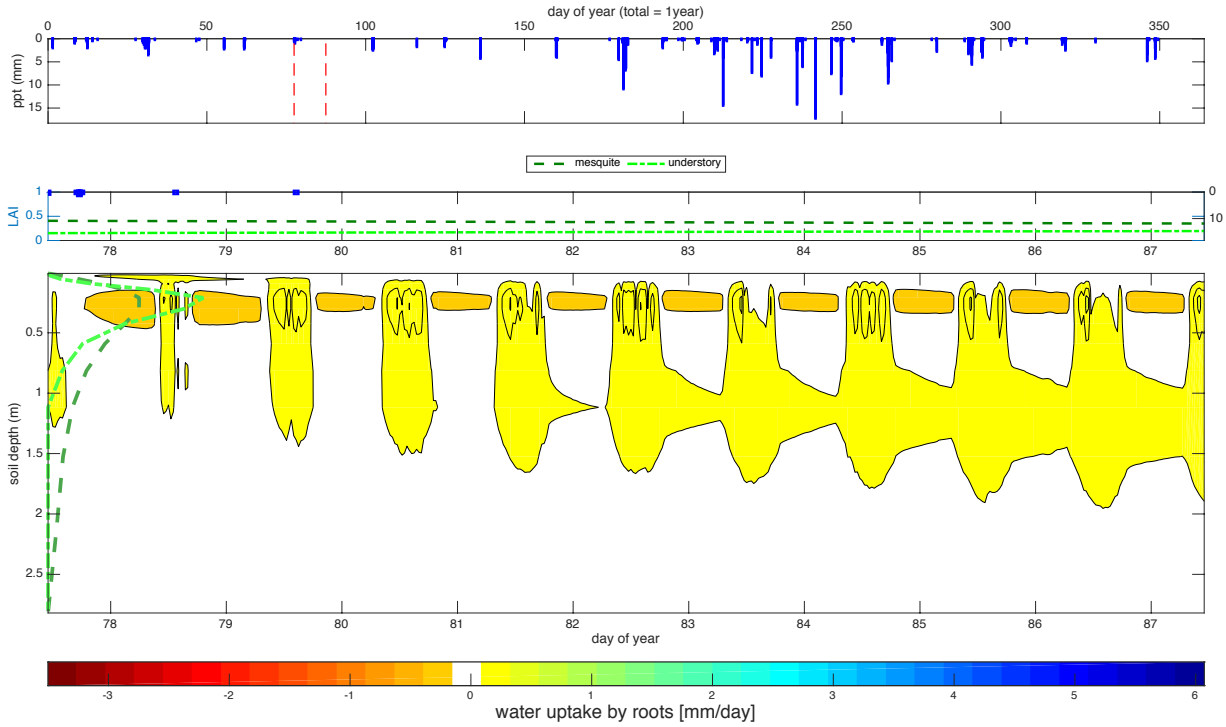

Figure 10: (top) 2015 precipitation with mark of 10 day window, (middle) Precipitation and leaf area index (LAI) of two species in 10 day window, (bottom) Water uptake by roots in different soil depth in 10 day window with root fraction distribution of two species

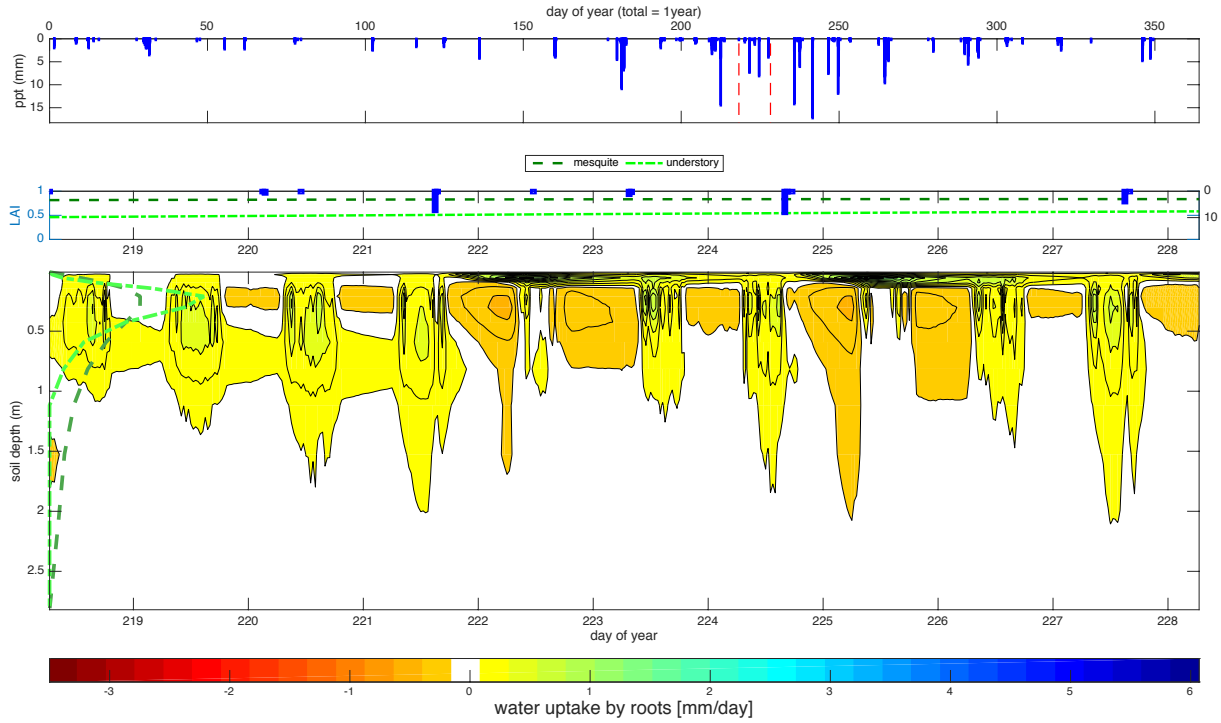

Figure 11: (top) 2015 precipitation with mark of 10 day window, (middle) Precipitation and leaf area index (LAI) of two species in 10 day window, (bottom) Water uptake by roots in different soil depth in 10 day window with root fraction distribution of two species

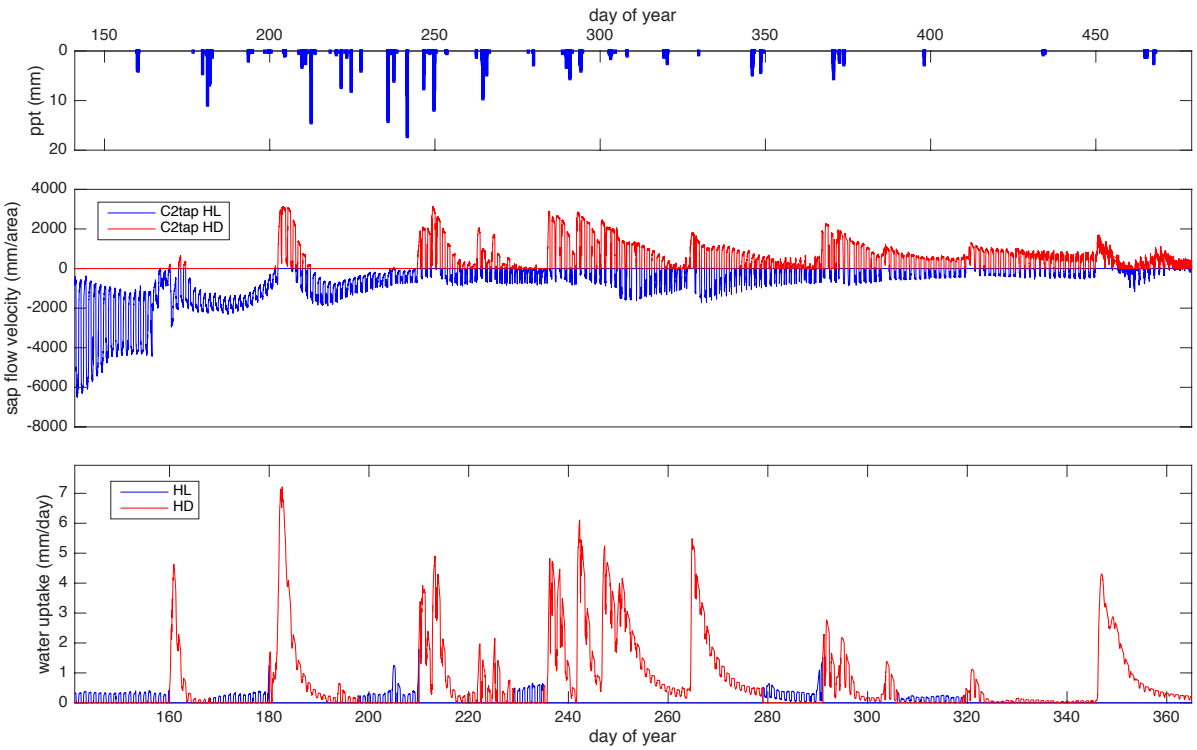

Figure 12: (top) 2015 precipitation, (middle) HL and HD of sap flow measurement at the mesquite trunk from the field, (bottom) HL and HD of model result

In Figure 12, the comparison between measured sap velocity and modeled result of shows that period and pattern of hydraulic lift and hydraulic descent are highly matching. Long HD period dominates throughout the year, especially in summer monsoon period. Compared to HD period, HL period is episodic and HL occurs between precipitations. The patterns of measured and modeled HR fluxes suggest that mesquite stores water through HD, when the soil moisture in shallow depth is abundant, and uses it for transpiration in the following dry season. The stored water through mesquite roots may be used in the following growing season. The result shows that during drought season, dry soil condition near the surface results in high water gradient between shallow and deep soil layers and enhances HR. Reduced soil water potential near the surface triggers HL fluxes so that soil moisture from the deep soil layers is transported to the shallow soil layer. However, less or absence of precipitation may result in low soil moisture and low soil hydraulic conductivity and may cause reduction in HR flux.

Even though the presence of HR is detected in measured sap flux and the field sap flux measurements matched with simulated result, the measured sap fluxes has not been converted to the same metric unit as simulated result. Therefore, quantitative analysis and comparison between measured sap flux data and simulated HR fluxes are not available yet.

4.2. HYDRAULIC REDISTRIBUTION IMPACT

4.2.1. Impact of HR on Evapotranspiration

The interaction between co-existing plants determines water dynamics in natural ecosystems. In this section, we consider different plants as a bulk of plants and examine the impact of HR on water dynamics. To analyze how plants utilize limited amount of water when HR is allowed, we simulated MLCan model for Santa Rita Mesquite site and calculate the amounts and percentages of water used in precipitation, HR, evaporation, and transpiration. Table 2 presents the amount of water annually used in different parts of water dynamics in Santa Rita Mesquite site in 2015.

The result from model simulation shows that 474.47mm of water is supplied to the system as precipitation and plants allocated 196.31 mm of water to deep soil layers through roots. Annually, 41.37% of precipitation is transported through HD. 13.52% of the water stored in deep soil layers through HD is redistributed back to shallow layers by subsequent HL. Assuming water supplied through HL supports evapotranspiration of plants, hydraulically lifted water supports 10.78% of plant evapotranspiration. If we only consider periods when HL occurs, hydraulically lifted water supports 23.7% of plant evapotranspiration. The rest of the water transported to deep soil layers may be stored in deep soil layer to be utilized in the following dry season or may be lost through infiltration.

Table 2: Comparison of case with HR and case without HR for 2015 data

	With HR	Without HR	Unit
PPT	474.47	474.47	mm
HD	196.31	-	mm
HL	30.08	-	mm
Evaporation	11.43	11.45	mm
$Transpiration_{mesquite}$	164.45	163.35	mm
$Transpiration_{understory}$	103.07	103.34	mm
ET	278.96	278.14	mm
HL/ET	10.78	-	%
$HL/ET_{during\ HL\ period}$	23.71	-	%
HD/PPT	41.37	-	%
HL/HD	15.32	-	%

4.2.2. Impact of HR on Different Species

By using the shared resource model (MLCan), we can examine competitive and facilitative dependencies between velvet mesquite and understory plants. To investigate how patterns of HR-induced soil moisture impact mesquite and understory function, we compare cases with and without HR. The comparison reveals the contribution of HR to transpirations of mesquite and understory. We examine how the presence and absence of HR impacts transpiration of co-existing plants. We plot transpiration with and without HR in Figure 13. The figure illustrates that the presence of HR does not necessarily benefit both mesquite and understory. The plot of percentage difference of transpiration between HR and no HR cases shows that the presence of HR increases mesquite transpiration in all seasons but impacts understory differently from season to season. The presence of HR increases understory transpiration during dry season and decreases wet season.

For mesquite, the magnitude of the percentage difference of transpiration remains small in dry season and increases in wet season. The increase in mesquite transpiration with the presence of HR during wet season indicates that mesquites use recent rain for transpiration. The small amount of increase with the presence of HR during dry season is due to lack of water supply. Less amount of water is redistributed in dry season when water supply from precipitation is limited and root conductance becomes smaller due to low soil moisture. The plot demonstrates that during wet season, mesquites redistribute water to store it in deeper soil layers where understory cannot access with shallow roots. HR inhibits understory performance and supports mesquite performance, which implies competitive relationship between mesquite and understory. However, during dry season, the understory plants use water from HL through mesquite roots.

The result indicates how understory uses hydraulically lifted water for transpiration. Particularly during dry periods, before summer monsoon, mesquite roots redistribute moisture through HR to benefit both mesquite and understory in spring. During this period, this redistribution increases understory transpiration and the system with multispecies demonstrates facilitative dynamics during dry period. The water potential gradient is enhanced due to low soil moisture near the surface and moisture is lifted to shallow soil layers for shallow rooted plants. However, during wet summer, the redistribution of water through mesquite roots decreases understory transpiration as presented in Figure 13. Understory transpiration with the presence of HR is lower than understory transpiration without HR. It may be due to shallow rooting depth of understory. The result also suggests that the water potential gradient between shallow and deep soil layers is greater than the water potential gradient between shallow soil layer and understory leaf.

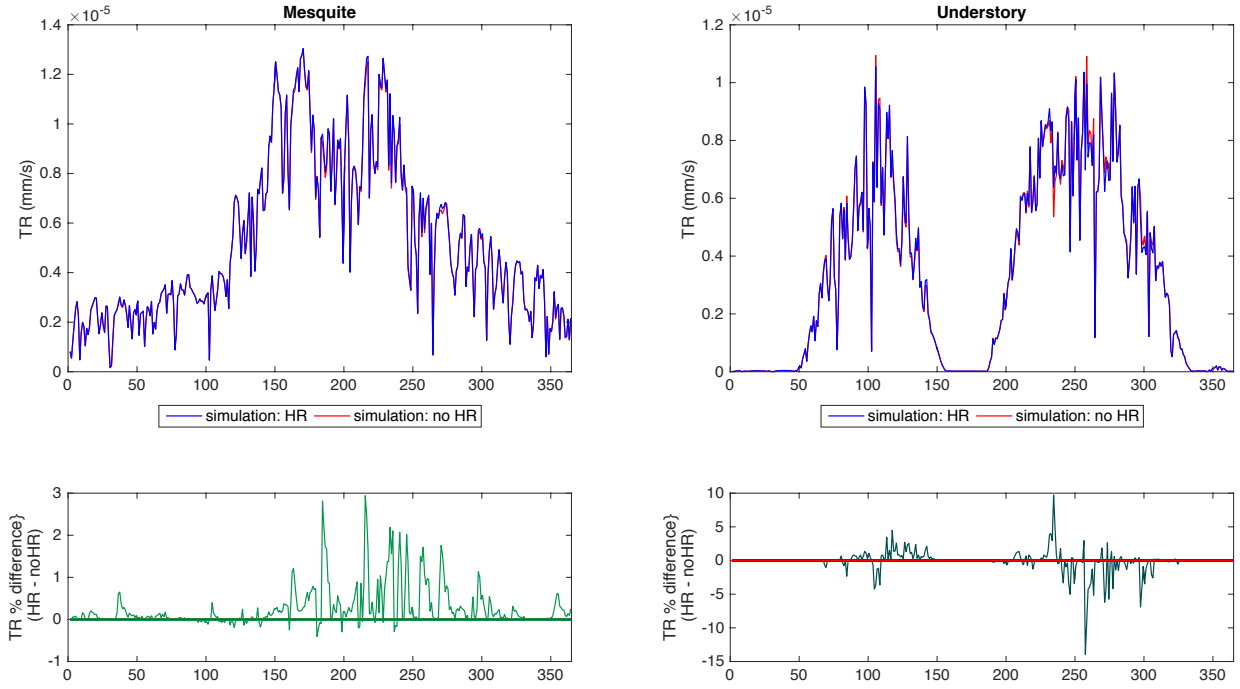

Figure 13: Comparison of transpiration between with and without HR cases

4.2.3. Impact of HR with Different Root Conductivity Ratios

Natural ecosystem has different factors that impact ecohydrological dynamics. In this section, we focus on one of the factors that affects HR flux: root hydraulic conductivity that determines the rate of water transport from soil to plants. Root hydraulic conductivity is a limiting factor of transpiration and HR fluxes. Radial and axial root hydraulic conductivities play an important role in the magnitude and direction of water transport through roots among different species. In this study, we examine how different ratios of root hydraulic conductivities of multiple co-existing species impact each species. Even though precipitation and shortwave radiation are two other factors that affect soil water potential and HR flux, we assume the precipitation and shortwave radiation remain the same for all simulated cases and examine the sole impact of root hydraulic conductivity on understory plants under the same environmental condition.

The ratio of mesquite and understory root conductivities is an important factor that determines how two plant species share resources in water-limited environment. In the study site, where access to deep-water resource is lacking, mesquite and understory both compete for water resource while only mesquite store water by HD after rainfall. Root conductivities of two species result in the different responses of two species. In this study, we simulated the model for the study site by changing the ratio between mesquite and understory root conductivities. We performed the simulation for four cases with different ratios of mesquite to understory root conductivities as (1) 1:0.1 (2) 1:0.5 (3) 1:1 (4) 1:2.5 (Table 3). For different cases, we assumed that the radial and axial root conductivities change with the same factors because obtaining root conductivities includes high uncertainty and it is challenging to measure root biomass, area and density in reality.

Table 3. Sensitivity analysis on different ratio of root hydraulic conductivities

Ratio of root hydraulic conductivities	Mesquite		Understory	
Mesquite : Understory	K_{rad} [s^{-1}]	K_{ax} [mm s^{-1}]	K_{rad} [s^{-1}]	K_{ax} [mm s^{-1}]
1 : 0.1			5×10^{-9}	2×10^{-2}
1 : 0.5	5×10^{-8}	2×10^{-1}	2.5×10^{-8}	1×10^{-1}
1 : 1			5×10^{-8}	2×10^{-1}
1 : 2.5			1.25×10^{-7}	5×10^{-1}

The result in Figure 14 shows that increasing understory root conductivity increases HR through understory roots and decreases HR through mesquite roots. In Figure 16 and 17, mesquite transpiration and photosynthesis increase with the presence of HR for all four cases. With higher understory root conductivity, mesquite transpiration and photosynthesis increase more.

HR affects mesquite and understory differently as the ratio of their root conductivities changes. With low understory root conductivity, understory loses the competition against mesquite for water and show decrease in transpiration and photosynthetic fluxes with the

presence of HR. The comparison of four different scenarios with different ratios of root conductivities suggests that HR process does not necessarily benefits both mesquite and understory. When the understory root conductivity is low (with the ratio of mesquite to understory root conductivities as 1:0.1), understory transpiration and photosynthesis are smaller with HR than without HR throughout the year. In such case, understory loses the competition against mesquite for water and shows decrease in transpiration and photosynthetic fluxes when HR is allowed.When the understory root conductivity is high (with the ratio of 1:2.5), the impact of HR on understory transpiration and photosynthesis differ throughout the year. During the dry season, understory transpiration and photosynthesis are larger with HR. However, during wet season, understory transpiration and photosynthesis are smaller with HR. These different results may be caused due to frequent HD in wet season when water is redistributed to deep soil layer where shallow-rooted understory cannot access.

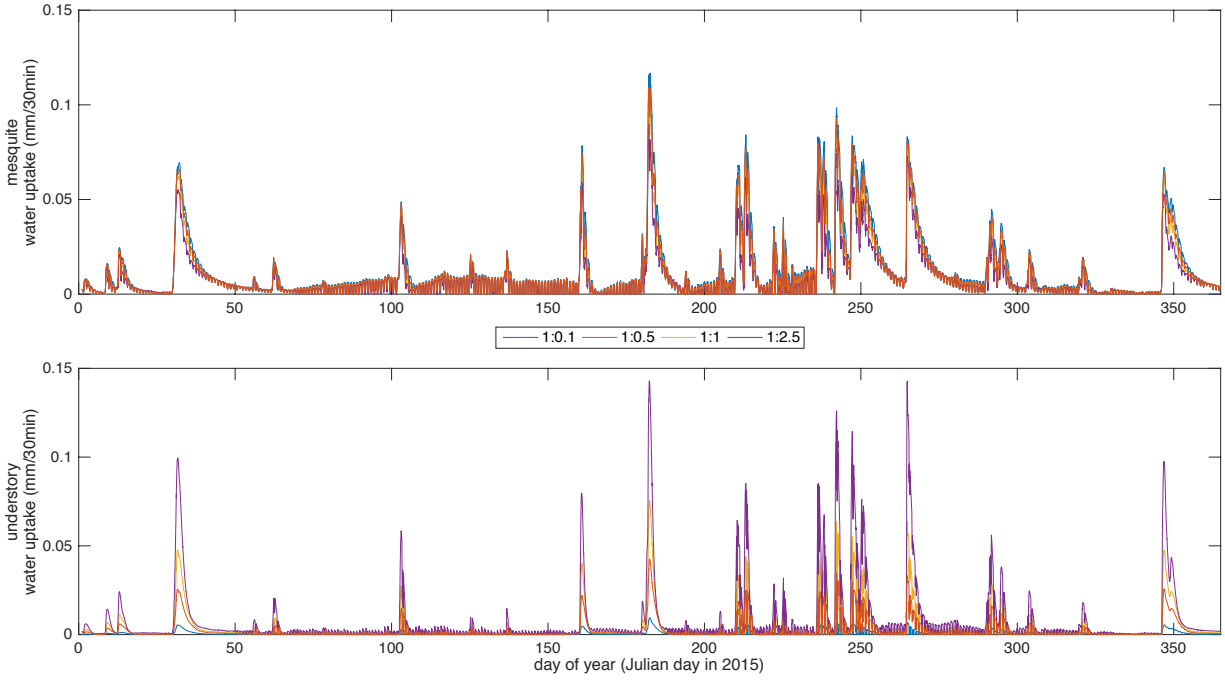

Figure 14: HR fluxes for mesquite and understory with different root hydraulic conductivities ratio

The water potential gradient that drives HR is dependent of leaf area index (LAI) of plants. During the daytime, plants use water for transpiration by opening stomata, which create water potential gradient between plant leaves and plant roots. Therefore, plants with high LAI create large magnitude of water potential between plant leaves and the soil. In the study site, mesquite LAI remains higher than understory LAI throughout the year. As a result, larger amount of moisture in the soil is transported through mesquite roots and reaches mesquite leaves. Note that around doy of 100, when the LAI of both species are around 0.3, the impact of small mesquite root hydraulic conductivity (in the first scenario with the ratio of 1:0.1) results in decrease in transpiration and photosynthesis. Around doy of 260, when the LAI of both species are around 0.6, the impact of changing mesquite root hydraulic conductivity is not significantly noticeable.

Although the belowground interaction between different species is sensitive to the maximum root depth of plants, the result illustrates that the ratio of root hydraulic conductivities of different species could play an important role in determining interaction in multispecies system.

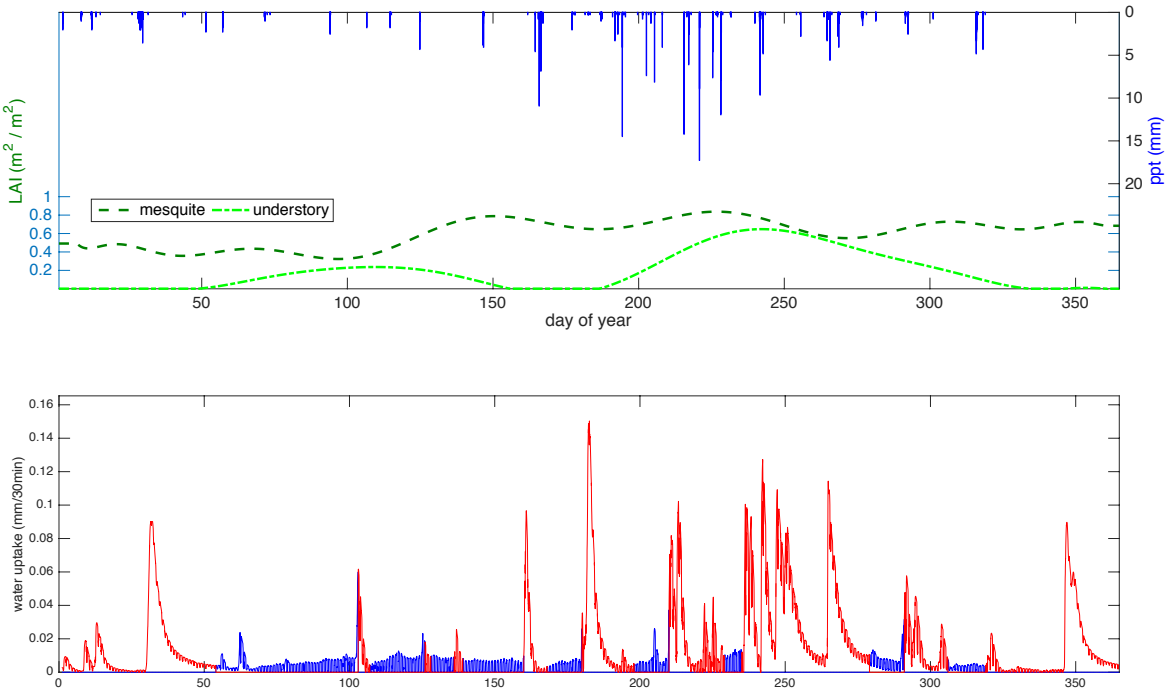

Figure 15: Leaf area index of mesquite and understory, precipitation and HR fluxes in Santa Rita Mesquite site

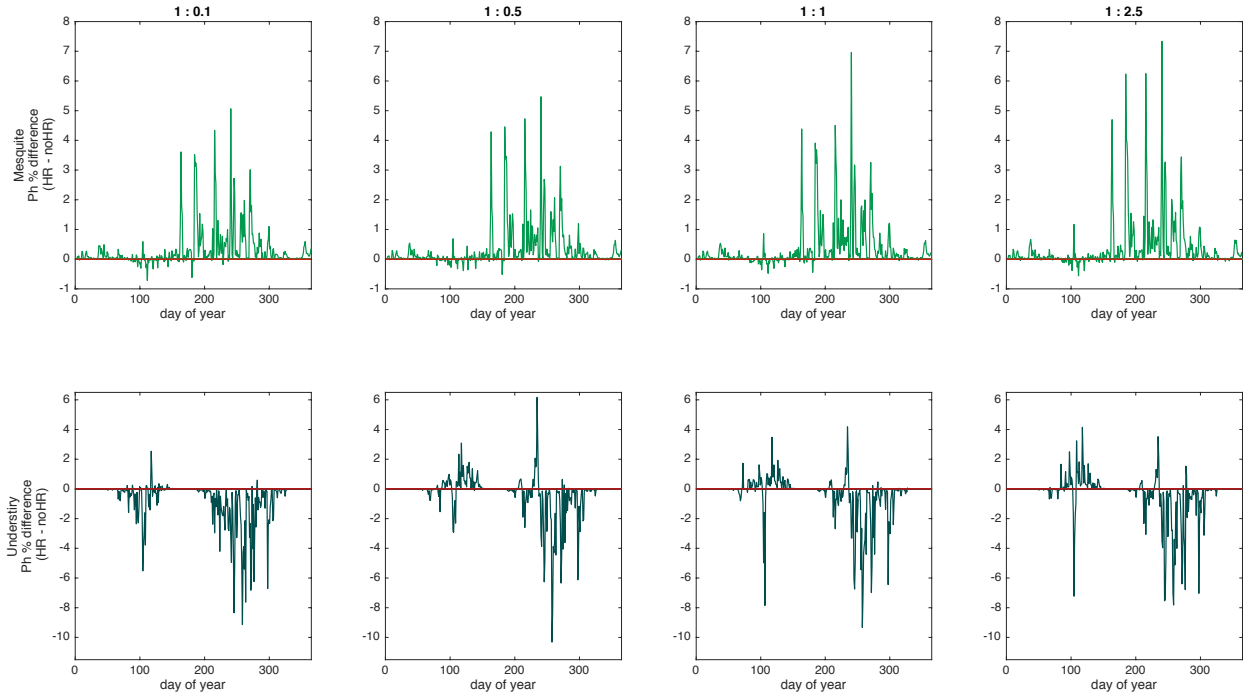

Figure 16: Percentage difference of photosynthetic flux between HR and no HR cases of (top) mesquite and (bottom) understory

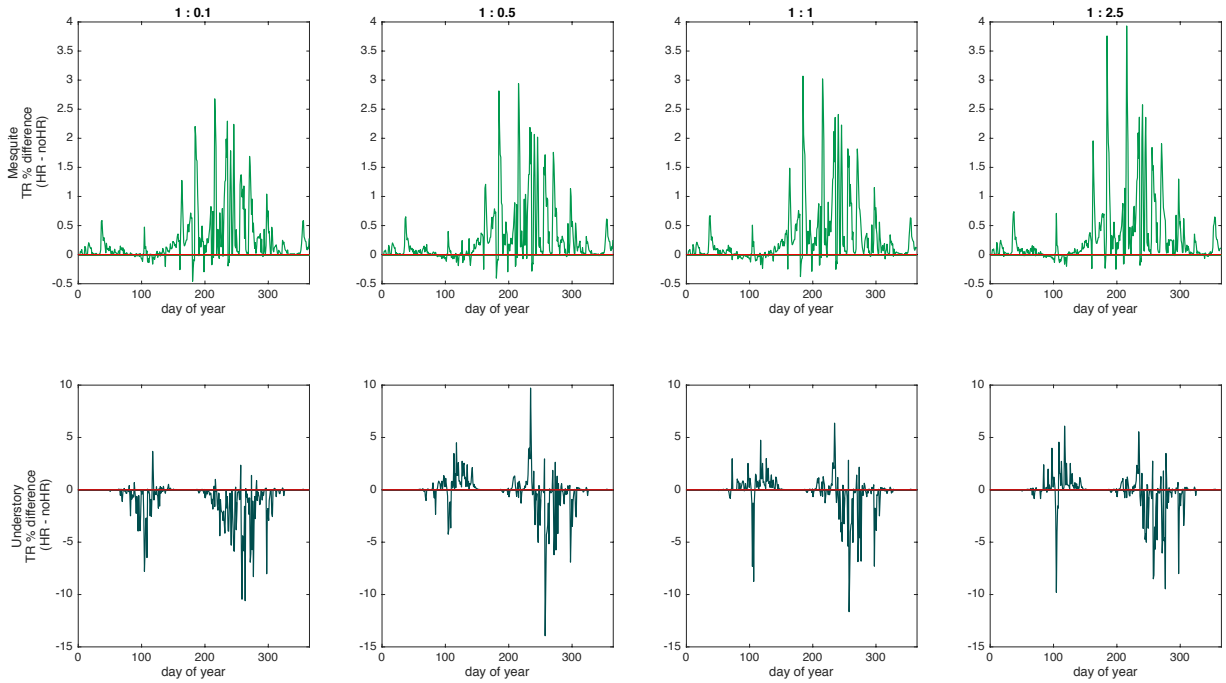

Figure 17: Percentage difference of transpiration between HR and no HR cases of (top) mesquite and (bottom) understory

4.3. SUMMARY AND CONCLUSION

This study examined seasonality of hydraulic redistribution in semi-arid region with co-existing multispecies vegetation. In this study we analyzed the impact of seasonality of plants and soil fraction and seasonality of HR on ecohydrological processes of different plant species. We captured seasonal interaction between aboveground and belowground water through HR and explored dependencies between co-existing plant species. Measured HR patterns were analogous to modeled HR patterns in timing. HD occurred right after precipitation in wet season and HL occurred between precipitation events. The study analyzed how two plants share and utilize limited amount of water by HR in both wet and dry seasons. The most important findings from the study are:

- Annually, 41.37% of precipitation is transferred to deep soil layer with HD and 15.32% of that is transported back to shallow soil layer with HL in dry season. Assuming water supplied through HL supports evapotranspiration of plants, HL annually supports 10.78% of mesquite and understory evapotranspiration. If we only consider periods when HL occurs, 23.7% of evapotranspiration is supported by HL. The rest of the water may be stored in deep soil depth to be used in the following dry season or may be lost to soil through infiltration.

- With the presence of HR, transpiration and photosynthesis increased for mesquite throughout the year. Despite of different seasons, mesquite transpiration and photosynthesis increased with HR. However, the occurrence of HR impacted understory plants differently in wet and dry seasons. In dry season, understory benefits from water hydraulically lifted through mesquite roots and in wet season, understory loses competition against mesquite for water and show decrease in transpiration. In wet season, mesquites deposit water to deeper soil through their roots right after rain to prevent water loss due to surface evaporation.

- The ratio of mesquite and understory root conductivities is an important factor that determines how two plant species interact and share resources in water-limited environment. The sensitivity analysis of different root conductivity ratios showed that high understory root conductivity facilitates water transportation through roots, which supports evapotranspiration and photosynthesis of co-existing plants. When the understory root conductivity is low, understory transpiration and photosynthesis are smaller with HR than without HR throughout the year. When the understory root conductivity is high, the impact of HR on understory transpiration and photosynthesis differ throughout the year. During the dry season, understory transpiration and photosynthesis are larger with HR. However, during wet season, understory transpiration and photosynthesis are smaller with HR. These different results may be caused due to frequent HD in wet season when water is redistributed to deep soil layer where shallow-rooted understory cannot access. With low understory root

conductivity, understory loses the competition against mesquite for water and shows decrease in transpiration and photosynthetic fluxes when HR is allowed.

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